Universal Desktop Fabrication

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Abstract. Advances in digital design and fabrication technologies are leading toward single fabrication systems capable of producing almost any complete functional object. We are proposing a new paradigm for manufacturing, which we call Universal Desktop Fabrication (UDF), and a framework for its development. UDF will be a coherent system of volumetric digital design software able to handle infinite complexity at any spatial resolution and compact, automated, multi-material digital fabrication hardware. This system aims to be inexpensive, simple, safe and intuitive to operate, open to user modification and experimentation, and capable of rapidly manufacturing almost any arbitrary, complete, high-quality, functional object. Through the broad accessibility and generality of digital technology, UDF will enable vastly more individuals to become innovators of technology, and will catalyze a shift from specialized mass production and global transportation of products to personal customization and point-of-use manufacturing. Likewise, the inherent accuracy and speed of digital computation will allow processes that significantly surpass the practical complexity of the current design and manufacturing systems. This transformation of manufacturing will allow for entirely new classes of human-made, peer-produced, micro-engineered objects, resulting in more dynamic and natural interactions with the world. We describe and illustrate our current results in UDF hardware and software, and describe future development directions.

1 Introduction

Humans and animals have evolved and live in an enormously complex dynamic system, the natural world. Lacking the vast computational resources necessary to explicitly represent and manipulate the complexity of the world, the animal and human mind developed the ability to represent objects implicitly, as simple, clearly delineated boundaries of space [1, 2]. It is hardly a surprise then, that traditional manufacturing and design processes assume that any given object or an independent part of a larger object is made from a single, homogeneous material. Raw materials extracted from nature are separated and purified so that they can easily be utilized in this framework. The lack of explicit computation and thus the homogenization of nature results in 'man-made' objects that clearly stand apart from nature.

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Over the past two decades, advances in digital computational power and the development of inexpensive and interactive three-dimensional modeling and visualization systems have extended the human capacity to conceive of and represent increasingly complex and optimal—more “natural”—objects. This has lead to the design of objects and software tools that do not respect the constraints of traditional manufacturing. At the same time, it has also instigated a family of technologies known as Rapid Prototyping (RP) or Solid Freeform Fabrication (SFF), better equipped to handle these new, “natural”, digital objects. SFF builds up complex three-dimensional objects directly from digital design data by depositing or solidifying material, layer by layer, under computer control. For the designer, the ability to simply “print-out” extremely complex and otherwise impossible to fabricate designs has driven the demand for RP/SFF technologies to produce not merely prototypes, but parts accurate and durable enough to obviate traditional manufacturing [3]. This general category of technology is referred to as Digital Fabrication (DF) [4]. The current state-of-the-art commercial DF systems allow net- or near net-shape mechanical parts with very complex geometry to be produced in a variety of engineering materials, ranging from thermoplastics to ceramics to high-performance metal alloys. Researchers are extending the range of what can be produced with DF processes to include sensors, actuators, electronics, power sources, and engineered living tissues, using ever more compact and automated systems that deposit multiple types of materials during the course of building a single object. As explicit design and manufacturing complexity and quality approaches that of the nature, it will be possible to fabricate objects previously considered too difficult or even impossible. Human-made objects will not stand apart but increasingly emulate and seamlessly integrate with the natural world.

This research and technology is sparking a transformation away from the limits of traditional manufacturing and centralized production [5] toward “Universal Desktop Fabrication” (UDF) —compact DF systems which can produce essentially any complete, finished, and functional object; not merely mechanical parts, but everything from birthday cakes, to complete cell phones (with batteries), to a human heart. Imagine an Internet of physical things, a 3D fax machine or the “replicator” from the science fiction TV series, Star Trek (Fig. 1). If such technology can be made accessible to individuals, it has the potential to revolutionize the limited ways humans construct objects, manipulate matter, and interact with the world. Individuals will not have to buy a generic, mass produced product shipped around the world to their local superstore. Instead they may choose to download an object, customize the design to fit their needs and 'print'. UDF lowers the financial cost and expertise required for invention, essentially placing an entire R&D laboratory on an individual’s desktop [6]. This will empower countless individuals to become creators of technology rather than passive consumers.

Unfortunately, significant barriers exist to the realization of UDF. The majority of intellectual property in the DF field is held by a few corporations, restricting competition and the identification of new applications, slowing innovation, and ensuring systems remain costly and complex. Commercially available systems are proprietary, and each system is optimized for one or two typically proprietary materials. Systems are not capable of varying the material composition freely through the part. Additionally, traditional human approaches to representing objects combined with intangible digital processes, having no physical limitations, have resulted in the development of popular

Fig. 1. Television's imaginary Star Trek Replicator

design software that is incapable of accurately representing real objects and thus an unsuitable platform for UDF, often proving problematic even for traditional manufacturing. DF and UDF hardware systems under development in research laboratories will soon be capable of producing functional objects with such extraordinary complexity of shape and material composition that existing digital design and engineering tools will no longer be able to represent them.

In order to surmount these barriers to the realization and dissemination of UDF, we are proposing an inexpensive and open research platform for its development, based on combining and extending several existing digital design and fabrication technologies and research projects. Inexpensive, desktop DF has demonstrably broad appeal [7]; therefore we expect that a UDF platform will readily attract intellectual capital from the flourishing online software and hardware development communities, vastly accelerating the rate of advancement and public adoption of the technology.

2 Characterization of UDF

In order to facilitate meaningful discussion, it is necessary to clearly define UDF. An important part of defining UDF is to understand the relationship between traditional manufacturing and UDF. The types and complexity of objects that these approaches can produce are quite different. In addition, it is necessary to identify and define the features and objectives required by UDF.

2.1 Simple Taxonomy of Representational Complexity

Understanding UDF means first understanding the ways in which humans have represented (and manufactured) objects historically and how with powerful computation these representations can change. To clarify for further discussion, a taxonomy of representational complexity should be defined. Using composition, construction and topology, three very general representational categories are suggested for describing real objects: *simple*, *complex* and *heterogeneous* (Fig. 2). As any real object viewed close enough can be considered extremely complex in construction, this taxonomy can also be mapped as various levels of granularity, from gross to highly detailed.

Simple representations have an explicit separation between different materials, and geometry tends to be smooth and continuous. Examples of objects that can be easily described this way might include such things as an egg or a swimming pool.

Complex representations are more natural in composition; various materials are distributed or intersect one another non-uniformly. Surfaces can be rough and detailed, often having deep valleys and peaks, as can be observed in the leaves of a tree or a geological body.

Heterogeneous representations exhibit a gradual change in material composition and associated properties throughout. Surfaces boundaries may be defused. All natural

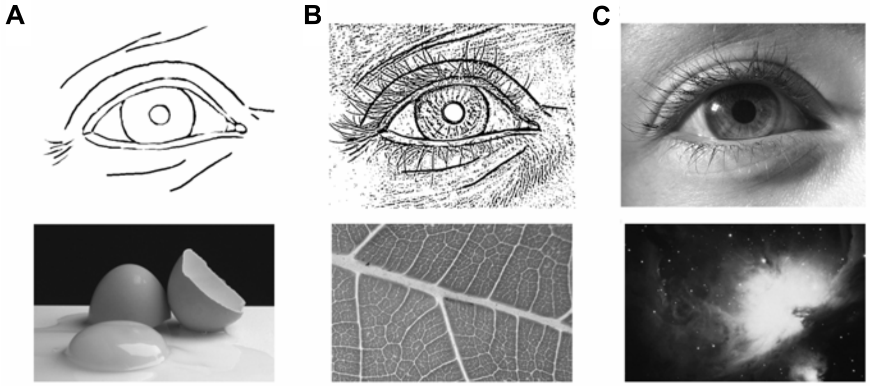


Fig. 2. The top set of images graphically illustrate the differences between the various representations: a) *simple* b) *complex* c) *heterogeneous*. The set of images below are examples of real objects that can be represented by these categories (however all real objects are truly *heterogeneous*).

and/or real objects regardless how simple they may appear are truly *heterogeneous*. It is not possible to represent many objects, such as a real human heart or diffuse nebulae, any other way.

Traditionally humans have defined objects using primarily *simple* representations and most, if not all, current industrial software modeling packages still represent objects in this way. Likewise, expensive RP and DF systems that exist primarily use a single material and are not comparable to the fantasy of a Star Trek replicator. These technologies are far from achieving a level of complexity close to that of the natural. Current DF software and hardware systems act like digitally controlled replacements for traditional manufacturing and while that alone has advantages, to fully capitalize on inherent potential in DF and the realization of UDF, robust, accurate and realistic descriptions of objects are necessary.

2.2 UDF Features

Academic and corporate research efforts are underway to develop, primarily single material, desktop DF systems [8, 9], invariably laying the foundation for UDF systems. UDF should not be considered as simply any '3D printer', but an inexpensive, personal system that, using a variety of materials, can fabricate a broad range of extremely complex and functional objects (previously thought unfeasible). It is important to identify what minimal properties such a UDF system would possess in order to be considered a viable public platform. These features should be understood as not just purely technical in nature but also reflecting the social and market aspects of such a platform. The 'Universal' nomenclature in the term signifies that it is readily available, easy to use, open to modification, and most importantly can fabricate a broad range of objects. The 'Desktop' aspects include low cost, small size and extremely low or zero toxicity and waste. A more detailed short list of features is presented here. This list is not necessarily meant to be exclusive or complete and mostly ignores the feasibility of the listed features. Instead, it serves both as a list of desirable objectives and as a reference point for further discussion.

Easy. Systems must be relatively simple to operate and use.

Free/Open. Some of the most successful, long term consumer desktop technologies today are built on free and open standards and collaboration. It has also shown to increase the rate of technological development [5, 6].

Detailed. The model and fabrication process must be fine enough that objects can obtain qualities and attributes of natural and real objects.

Heterogeneous. The system must be able to represent *heterogeneous* objects with a broad range of materials and fabricate new materials and composites.

Self-Assembly. Digital and/or self-assembly methods, including physical error-correction, will enable the fabrication of objects with tolerances superior to those of the fabrication machine itself, and the production of multiple copies of a given object with near-perfect fidelity.

Inexpensive. The complete system price, power consumption and cost of materials must be roughly similar to other desktop computing technology.

Fast. The fabrication process must be cost competitive with traditional manufacturing approaches when the design freedom provided by UDF is accounted for.

Compact. Systems must be small and lightweight (perhaps at some point it may not require a separate machine for fabrication).

Safe. Hazardous and/or toxic processes are unacceptable for low cost desktop systems as it drives up cost and more importantly can harm users and environment.

Disassemble. Systems should be able to recycle locally by disassembling objects back into raw materials.

3 Related Works

Most available DF systems, if not all, are oriented toward tightly integrating with existing and limited commercial Computer Aided Design, Engineering or Manufacturing (CAD/E/M) frameworks and representations. These commercial systems are not designed to model *heterogeneous* objects. This practical bias places focus on the fabrication of homogeneous and *simple* objects, ignoring *complex* and *heterogeneous* ones. Existing systems usually do not attempt to rethink DF as a whole, instead they rely on traditional CAD systems and independently solve hardware or software issues. The creation of a complete UDF system requires approaching the problems of DF anew and thus it becomes necessary to develop both the hardware and software components in concert. Most existing systems do not take such a holistic approach and are not interested in the same objectives as UDF. The following sections discuss various systems and research projects oriented towards inexpensive and/or *heterogeneous* fabrication.

3.1 Hardware

A common method to currently manufacture blended multi-material objects is by using complex injection molding processes whereby one material is injected into a mold, followed by another material. Specifically calculated and computer controlled temperatures and amounts yield objects with an expected smooth transition of material [10]. Although this system produces *heterogeneous* objects in some sense, there is a lack of precise control over the internal composition and complexity of the objects. In addition, injection molding requires non-reconfigurable tooling, typically very expensive and time consuming. This favors fixed manufacturing and mass production, making it unsuitable as a DF technology.

Most DF hardware systems use a Solid Freeform Fabrication (SFF) process [11], by slicing a shape into cross sectional layers and adding a layer of material at a time to build up an object. There are a wide range of SFF methods and techniques. One method is building each layer with a target material and building support structures for overhanging features in the same material or another, explicitly sacrificial material. After fabrication, the support material is removed by another process. These "fabricated support" SFF methods include Fused Deposition Modeling (FDM), stereolithography, and Laser Engineered Net Shaping (LENS). Another method involves applying a layer of typically powder or laminar target material to the entire working surface, and selectively binding or fusing the material within the cross-section of the desired part to prior layers. Rather than building a separate support structure, this method utilizes the unbound/unfused material for supporting overhanging and unattached features. Such methods include 3D printing, laminated object manufacturing, and selective laser- or electron beam-sintering. Other methods include hybrid processes such as shape deposition manufacturing [12] that uses several staged processes, including more traditional CAM processes like milling, to produce high tolerance parts. Most of these methods, due to the extensive tuning of the fabrication process for a specific material and the restrictions of existing CAD systems are limited to the fabrication of homogeneous objects. There are a few notable exceptions.

Although the Z Corp Spectrum Z510 is not actually a multi-material fabricator, it has the capacity to print any color at any point in the object. This capability is primarily used to print the surface of the object with color in the form of a 2D image texture map. However this is very useful as a way to physically visualize various properties of an object, including material, by mapping various properties to colors. The Z510 does not directly produce functional objects, as the bound powder parts are quite fragile. Infiltration with epoxy or cyanoacrylate resins can render them robust enough for light mechanical use.

Most of the systems that produce *heterogeneous* functional objects are somewhat experimental, extremely specialized and expensive, such as the Optomec's LENS 850-R. This fabricator is capable of producing metal objects from a variety of alloys, as well as fabricating composites and functional gradient materials. It has been designed as an aerospace and military solution for the limited production of new parts and rapid repair of specialized parts.

Apart from such expensive and exotic systems several commercial companies are in the process of producing SFF systems targeted at small businesses and individual users. Desktop Factory has developed a '3D printer' which is currently the lowest priced commercially available system [8]. However, it prints only single material objects with fairly low resolution from a composite plastic powder.

Other more inexpensive and dynamic systems are under development. Recent research has resulted in a few desktop SFF systems using a "do it yourself" (DIY) approach. These systems are extremely inexpensive (supplanting money by time invested) and flexible. One such system of notoriety is the RepRap Project [9]. This project's stated goal is the creation of a self-replicating machine. However, the project has produced an inexpensive FDM fabricator capable of printing usable plastic parts. Due to the DIY/free-source nature of the project, the hardware is also easily extensible and all the plans, specifications and modifications are placed on the Internet and freely downloadable. It is possible for the hardware to be adapted to use various fabrication processes and materials. This project and fabricator have specifications compatible with that of UDF.

3.2 Software

As of yet, no complete commercial 3D CAD/E/M package for *heterogeneous* objects exist. Instead designers and engineers are limited to creating homogeneous parts and multi-material assemblies. However, over the last decade, volumetric and *heterogeneous* representations of objects have received much attention in shape modeling and CAD/E/M research [13]. The rest of this section will discuss various systems for the representation of object's properties (or materials). A diverse group of solutions has been developed. In general these can be divided into two categories: *discrete* representations and *continuous* representations. Additionally, several advanced representations exist. *Composite* representations can be identified as a collection of sub-objects where each separate object can be *discrete* or *continuous*. *Hybrid* representations can use both *discrete* and *continuous* in simultaneous conjunction. *Discrete* models can produce detailed and complex property distributions, but at the cost of accuracy, practical resolution and usability. Examples of such systems include voxels and volume meshes. Such models include voxels and volume meshes. *Continuous* models are based on rigorous functions describing exact geometry and are much more accurate and compact and include control features, control points, and real functions. Several of these methods are worth discussion in more detail.

Voxel based representations are well established (especially in medical visualization) and for more than a decade have been proposed for modeling and fabrication [14]. These representations are good for *complex* objects and useful for representing volumetrically scanned data from magnetic resonance imaging or other such technology. It is also easy to implement hardware optimization and parallelization for voxels. However it is not easy to edit the large voxel sets which are required to reduce aliasing and make smooth or high quality objects.

Unlike voxels, control point based *heterogeneous* modeling is continuous, utilizing Bezier, B-spline volumes and tri-variate NURBS [15, 16, 17]. These representations are fairly compact, exact and can represent *complex* and *heterogeneous* material distributions. However the representation is only applied to property distribution. The geometry model usually relies on the standard CAD/E/M representation, Boundary Representation (B-Rep) [18, 19], and thus requires two completely separate processes when modeling geometry and composition. In addition, parameterization of the object as a whole becomes problematic, limiting the complexity and abstraction of designed objects and reducing usability.

Real function based properties can also be used to represent the distribution of materials inside B-Rep geometry [20, 21]. When applied in this way, real functions, have the same advantages and drawbacks as control point based methods, except more detailed and constructive modeling of materials and properties is possible. However, real function based properties can also be applied to real function based geometry [22, 23, 24]. In this case modeling and property assignment can happen simultaneously in a singular uniform environment. This advantage has a drawback. Compatibility with standard CAD/E/M becomes a problem, as it can be very difficult or impossible to import certain kinds of B-Rep based data into a real function model.

4 Implementation Problems

Practical research aimed at developing complete usable UDF systems is in its infancy. As such, many known (and unknown) problems face UDF technologies. Some general problems are presented in the subsequent section. Many of these problems are not discussed in detail, but are simply presented as a basis to understand the complex technical challenges involved.

Accessibility. Current fabrication systems are physically large and heavy and often require special facilities. Cost and operation of complete systems still remains prohibitive for individuals or even small research teams. Specially manufactured and expensive materials, often only available from the vendor, are required for operation. The machine maintenance and operation requires an expert. Despite the high cost of operation, many systems are slow, some take days to complete a single object.

Accuracy. Most of the current DF systems have poor resolution and aliasing can be physically observed and felt by touch. Practically, these systems operate at a scale somewhere not far below the millimeter. In order to produce truly *heterogeneous* objects with smooth details and advanced functionality, system resolutions must achieve micrometer scale. New problems present themselves at this scale, such as accurate system control, speed of fabrication, maximum size of objects, and repeatability of fabrication and data representation. Many of these problems have already been solved by the desktop printing industry. However, overall this still remains a complex suite of machine design and control, and materials science problems.

Complexity. It is important to note that while some progress has been made in developing inexpensive desktop fabricators (see section 3), *complex* or *heterogeneous* fabrication still remains elusive on low cost machines. Even using very expensive frameworks it is problematic and an active area of intense research. Most systems use a single material and operate using mesh or control point data, often limiting the ability of hardware in the complexity and/or accuracy of the objects they can build. This is because machines are painstakingly optimized for each material, different materials often have conflicting processing requirements, and because traditional 3D CAD software is difficult to use, expensive and fundamentally incapable of modeling real objects (i.e. *heterogeneous* objects).

Health/Environment. Many of the first RP processes developed used hazardous processes and/or materials, including carcinogenic resins, and high-powered lasers. There has been some progress recently, however hazards still remain an issue. In addition many of these systems, if used by millions of people, would have a profound environmental impact. Mass production facilities are often compelled and sometimes financially motivated to collect and recycle by-products of manufacturing, and economy of scale can make this relatively cost effective. It is unclear whether waste management can be cost-effectively rescaled for personal fabrication. In the Age of Information and the 'paperless society', humans are not using less paper, they are using even more as it becomes a temporary medium to exchange information [25]. Unlike the paper printing process, the objective of UDF is not to exchange information (which at some point arguably could be replaced 100% by digital processes) but to fabricate material objects effortlessly. Also, unlike the paper printing processes, using the current processes available for *heterogeneous* fabrication, there is still no clear answer on how to recycle the resulting objects or better yet disassemble them back into raw materials. Improvements to *heterogeneous* fabrication allow ever more intimately combined materials, exacerbating the disassembly/recycling problem.

Standardization. In addition to the strictly technical issues identified with the current research, there are also issues surrounding standardization and development. Little standardization or global collaboration exists at present and what does exist is poor and outdated (for example the STL file format). Even though the idea of assembling objects digitally is a very popular topic, there does not seem to be enough open development or collaboration. As it seems to be currently true for many fields in IT, much of the work done over the last decade on DF has been by corporations and now even academic institutions that are closely guarding and protecting their inventions as secrets, [26] stifling technology wide innovation.

A main focus of the current research is solving those issues related to accessibility and complexity. In the next sections more details are provided on these two topics.

4.1 Problem of Accessibility

Commercial DF technology is still focused on producing passive mechanical parts in a single material, and the emphasis of commercial R&D has been on improving the quality, resolution, and surface finish of parts, and on broadening the range of usable materials. Growth in the market for and capability of commercial DF technology has been disappointingly slow – commercial systems have been available for more than two decades, yet worldwide annual sales of systems are still measured only in thousands. At present SFF systems remain very expensive and complex, focused on production of single material mechanical parts, and used primarily by corporate engineers, designers, and architects for prototyping and visualization and a limited range of end use parts. These factors are linked in a vicious cycle which slows the development of the technology: Niche applications imply a small demand for machines, restricting commercial R&D and adoption of the new capabilities demonstrated in the laboratory, while small demand for machines keeps the machines costly and complex, limiting them to niche applications.

4.2 Problem of Complexity

Currently most, if not all, major industrial grade CAD/E/M software represents objects as a boundary or division of space, or B-Rep. In practice this means a hierarchical tree of divisions of 2D surfaces in 3D space, that for 'solid' objects (which are necessary for fabrication), should define a closed object. B-Rep models fail to define the internal composition of objects. In other words, traditional 3D models are represented as empty spaces inside a zero thickness 'shell'. Fundamentally this means it is not possible to exactly represent natural, real objects in the world. However, as long as such B-Rep models are truly closed, have correct normals and with additional modeling data (often added in a separate process), they can be used to fabricate some types of multi-material objects. The process is computationally and memory intensive; creates large data sets and can be problematic (depending on the objective). This becomes more evident when fabricating *complex* or *heterogeneous* objects. The utilization of B-Rep geometry for multi-material fabrication is most applicable for modeling *simple* objects with clear divisions between materials where each material in an object is modeled as a separate part.

If a given system or technology is provided poor input, then often the capabilities and output is also poor or at least problematic (on rare occasions input to a system can be 'improved'). Thus, if a computer can not represent real objects in a universal and functional manner, then it will be problematic to develop a general method for digitally fabricating arbitrary objects and an average technology user will not be able to practically utilize DF systems. Even with dynamic manufacturing methods like local composition control and SFF, currently available software does not operate in truly *heterogeneous* manner. These software systems, in part due to human thinking, simplify reality as sets with clear boundaries. In contrast to such simplification, natural and real objects have no such boundaries; they are *complex* and *heterogeneous* in construction. For example, humans generally describe a watermelon as a green skin with a red inside (Fig. 3a), when in fact a watermelon's 'skin' is thick, irregular, mostly white and it is unclear where it ends fading from green to white to pink, and where finally the fibrous red fruit begins (Fig. 3b).

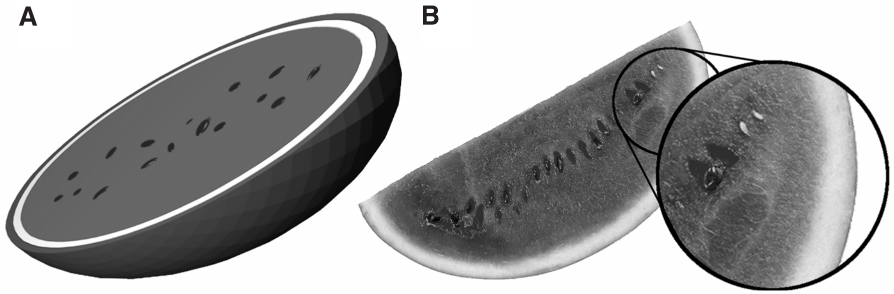


Fig. 3. Watermelon informatics: (a) traditional *simple* CAD model, (b) real object with *heterogeneous* internal material distribution

For a more practical explanation, imagine an architect using traditional CAD software and modeling a wooden house in 3D. It will finally be represented as 2D polygons set next to each other in 3D space, not as real objects and materials with connections. The small individual cuts of wood, the grain of the wood and the existence of nails or glue go unrepresented. In fact, far from modeling the material properties of a building, in practice most architects create models in 3D as a separate process (from the creation of building plans in 2D) for visualization of design only. The simplification of objects is not the fault of software but an accepted and necessary process of human thinking and design. Part of the traditional design and manufacturing processes has been to fill in the missing details or errors (often not well documented) in design as objects are built for the first time. There has always been a gap between what is designed and what is manufactured. However, due to modern information and computation technology, this needs not be the case and results of this approach are already visible in design. Moreover, as the computational ability to explicitly define exact objects increases, whole new categories of human-made objects and design previously unconsidered or improbable become possible. Explicitly designing objects that can self-repair or flora capable of generating electrical power, enter the realm of possibility. A major barrier preventing the micro-fabrication of such objects is the lack of computationally uniform and robust representations and frameworks that represent both property (including material) distribution and geometry simultaneously. A designer should be able to define the geometric boundary of an object as unclear or defused and indicate at any given point in an object, a variety or properties including but not limited to material composition. Simple and sharp interfaces are replaced by complex and smooth variations. In order for this to be practical it must also be done in a compact and accessible method. This is one of the most difficult challenges facing the fabrication of *complex* or *heterogeneous* objects.

Recently to compensate for the limitations of B-Rep, researchers have been looking at novel ways to combine B-Rep geometric data with additional data to describe material distributions (see section 3.2). Thus far extending or patching formats that fundamentally are incapable of encapsulating the nature of real objects has serious limitations. For example, even accounting for the fact that most fabricators are designed to print in one material, software prevents them from printing extremely geometrically *complex* and large objects at high resolutions, like an internally accurate skull, including the porous features inside the bones and teeth. Moreover, how would a user be able to reasonably create or modify such a data set using traditional software? To fully take advantage of digital fabrication technologies, future representations should be able to operate on both the surface geometry and internal composition in a uniform, compact, and consistent manner.

5 Approach

As stated previously, given the enormity of the task to develop a fully functional UDF system, it is not possible at this time to seek solutions to all the problems identified. For example assembling objects at a nanometer scale, which is required to make many desirable objects such as microelectronics, has not been broached by this research. Indeed many of the issues surrounding these problems remain unclear and additional problems are expected to be defined. Instead the primary objective of the research presented here is to work on the most accessible problems, develop solutions to these and most importantly to develop an inexpensive and functional open platform for collaboration and experimentation. It should be a generalized fabrication system using inexpensive, available, open technologies that exist today, resulting in a low cost, complete, usable, *heterogeneous* SFF system.

The open platform should not be limited to just companies, institutes and universities, but instead to any person or organization that has a small budget and access to the Internet. As the Internet has repeatedly demonstrated, having many diverse groups and people developing a technology is an extremely successful development model. To further rapid and diverse collaboration, Free and Open Source Systems (FOSS) methodology and licenses have been adopted.

Continuing in this line of thinking, the hardware system should be easily customizable and use an unlimited variety of inexpensive and easily attainable raw materials for printing. The design of the system should be simplified so that the construction of the hardware platform uses various inexpensive parts, is available online, and can be assembled together in a few days. In addition, users should be able to use a wide variety of easily attainable consumer materials.

Many methods now exist to fabricate objects digitally such as FDM, ink-jet deposition and photo static methods. The experimental UDF system should not be limited to a single DF method, instead it should allow a variety of tools and methods to be developed and used, perhaps even several different methods used to make a single object. The system should be able to dynamically mix or assemble several materials and/or processes together for a given resolution at any arbitrary location in the object.

To understand and finely control a *heterogeneous* object's design, users should be able to edit both the geometry and composition of *heterogeneous* objects, by a similar or identical method at the same moment. It should not require separate modeling stages for geometry and then composition, making it impossible for a user to visualize the composition of an object while modeling the geometry or forcing the user when making a modification to step though a complex processes every time. Likewise for fabrication, the system should have a framework able to identify geometric features and material composition in a uniform method. In addition the resolution and complexity of modeling and fabricating with the system should only be limited by the current computational power available.

Thus a simple, compact and uniform system that simultaneously represents both internal composition and object geometry as a so-called “implicit” model with real continuous functions is required. Function-based modeling is a necessary core technology for UDF (and perhaps the increasingly digital future), that is leading towards interactive modeling of *complex* and *heterogeneous* objects without requiring an explicit specification of the internal configuration. This will provide the means to develop and operate nanometer scale engineering, simulation, design and fabrication systems. The proposed system will use direct fabrication from an object's compact function representation and not from intermediate and degrading file formats like STL. These formats not only degrade the topology but more importantly have no way to represent real *heterogeneous* objects. Although it is theoretically possible for several STL models to be combined to represent a *complex* multi-material object, the data size would make storage and computation prohibitive. A functional UDF system must adopt a procedural, function based approach to modeling and fabrication. However, it should also be able to adequately accept discrete legacy data in a uniform way.

Several existing research efforts have already laid the foundation for UDF. Two projects, Fab@Home (FaH) and HyperFun (HF), as in “hyper-dimensional functions”, are both advanced research efforts in their respective areas. It is also interesting to note, but perhaps not surprising that they are both FOSS, utilizing the concepts of peer production to simultaneously speed up production cycles and democratize innovation. The HF project is a good choice as an underling representational foundation for UDF development, able to digitally describe, create and modify any object or environment. The HF project lacks a DF hardware component, however. FaH is a good choice for a DF hardware platform, as it is simple and inexpensive, yet capable of multiple-material deposition and easily extensible. FaH includes CAM software, but lacks integrated *heterogeneous* digital design and fabrication tools. Better than either of these projects alone would be a single system integrating design, engineering, and manufacturing.

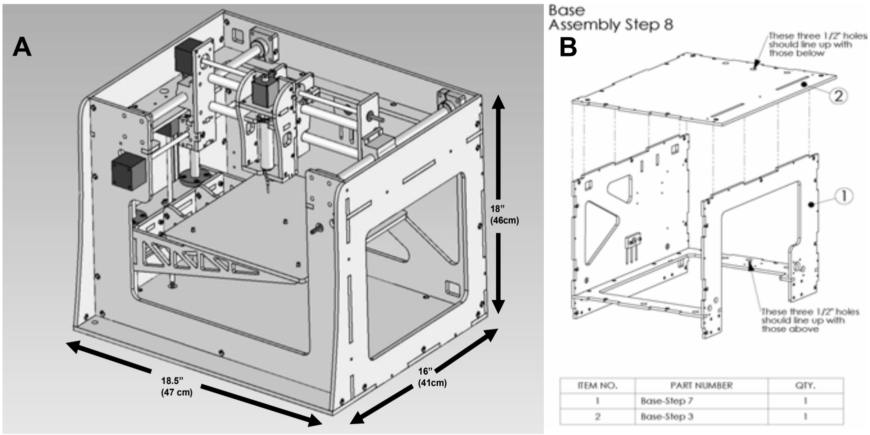
6 Previous Work

The FaH project and team has developed a usable low cost DF robot, and a uniform volumetric modeling system has been developed by the HF project. Both of these projects have years of development behind them and provide a developmental foundation for further work.

6.1 Fab@Home

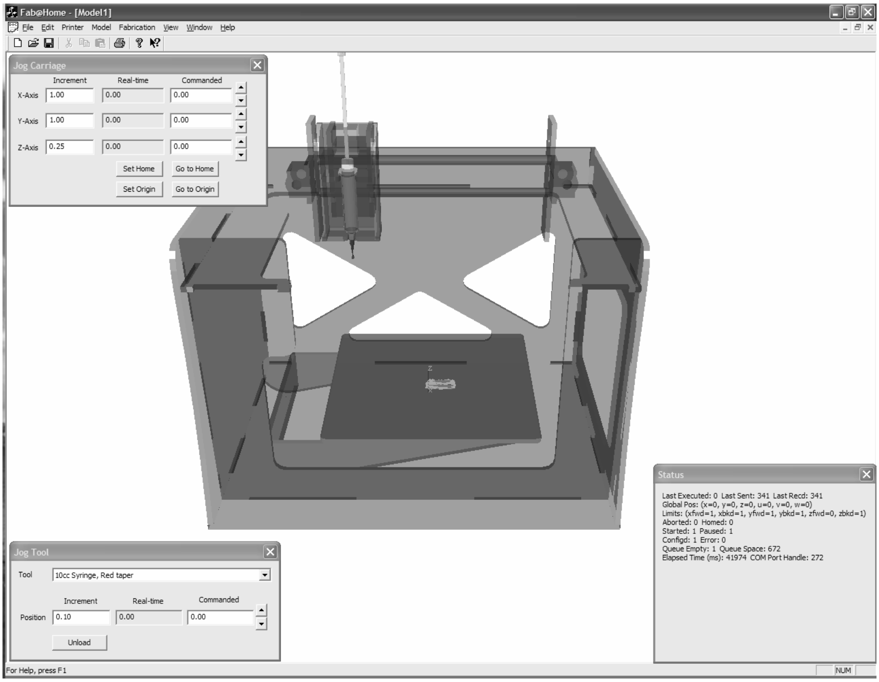
The FaH Project has been inspired by the FOSS approach employed by the RepRap Project. The aim of FaH is to put DF technology into the hands of the maximum number of curious, inventive, and entrepreneurial individuals, and to help them to drive the expansion and advancement of the technology. To achieve this, we have developed an open source, low-cost, personal DF system, which we call the “FaH Model 1” (Fig. 4a), and a user-editable “wiki” website to publish the system designs and software, and to foster a collaborative user community. The parts for the Model 1 kit has a rough cost of $2300 (USD). It includes a free, open-source CAM application which controls the hardware, and processes STL files into manufacturing plans. Almost any room-temperature liquid or paste can be used as the deposition material. Only basic hobbyist tools and skills are required to assembly and use the Model 1 and its software. We have endeavored to make obtaining, assembling, using, and experimenting with the Model 1 as simple and intuitive as possible; the website provides step-by-step ordering, assembly (Fig. 4b) and operational instructions, and an interactive three-dimensional, WYSIWYG, CAM application (Fig. 5).

This custom CAM application which imports individual or assemblies of tessellated geometry (polyhedra) in the STL file format, generates hardware executable manufacturing plans, and controls their execution on the fabrication hardware. The system operator uses a Graphical User Interface (GUI) to specify with which material and tool combination each polyhedron should be fabricated. The tool path planning consists of slicing each polyhedron according to the road thickness associated with its particular material/tool combination, offsetting resulting boundary polygons by a half of the material deposit width for the material/tool, and filling enclosed areas with raster fill (hatch) paths. Slices (containing paths) are then sorted by their height and executed, with the software prompting the operator to change the material and/or tool as required. The hardware currently allows only one tool/material combination to be mounted at a time, and changes are manually executed, so although the use of multiple materials is possible, time and labor become a significant factor for detailed objects, such as batteries. To reduce this cost, we have developed a technology, dubbed Backfill Deposition. In practice, as geometry data describing component parts of a device such as a battery are imported into the fabrication system software, the operator may use the GUI to assign a sequential fabrication priority to each of the parts.



ITEM NO.	PART NUMBER	QTY.
1	Base-Step 7	1
2	Base-Step 3	1

Fig. 4. The FaH Model 1 design. (a) 3D CAD model of an assembled Model 1; (b) An example of assembly instructions available via the project website (http:// www.fabathome.org).



	Increment	Real-time	Commanded
X-Axis	1.00	0.00	0.00
Y-Axis	1.00	0.00	0.00
Z-Axis	0.25	0.00	0.00

```
Last Executed: 0  Last Sent: 341  Last Recd: 341
Global Pos: (x=0, y=0, z=0, u=0, v=0, w=0)
Limits: (xfwd=1, xbkd=1, yfwd=1, ybkd=1, zfwd=0, zbkd=1)
Aborted: 0  Homed: 0
Started: 1  Paused: 1
Configd: 1  Error: 0
Queue Empty: 1  Queue Space: 672
Elapsed Time (ms): 41974  COM Port Handle: 272
```

Tool: 10cc Syringe, Red taper

	Increment	Real-time	Commanded
Position	0.10	0.00	0.00

Fig. 5. The FaH CAM application displaying a model ready for fabrication, dialog boxes for positioning and real-time status information

The SFF system will fabricate higher priority parts of an assembly to their full height prior to fabricating lower priority parts, in contrast to strict layered fabrication. This can reduce the number of tool changes in some cases from one per layer, down to one per STL file (or part). The priority will be obeyed by the system except where doing so would violate the relationship of one part supporting another. Additionally, this option facilitates fabrication of objects which contain or are made from liquid materials. It allows the fabrication system to construct a container before filling it. For example, the case of a battery can be given a higher priority than the materials to be deposited into it, and it will be completely fabricated to its full height before the deposition of the other materials begins.

The Model 1 machines have been used to make *simple* functional objects (Fig. 6). A user-editable “wiki” website facilitates publishing the designs and documentation.

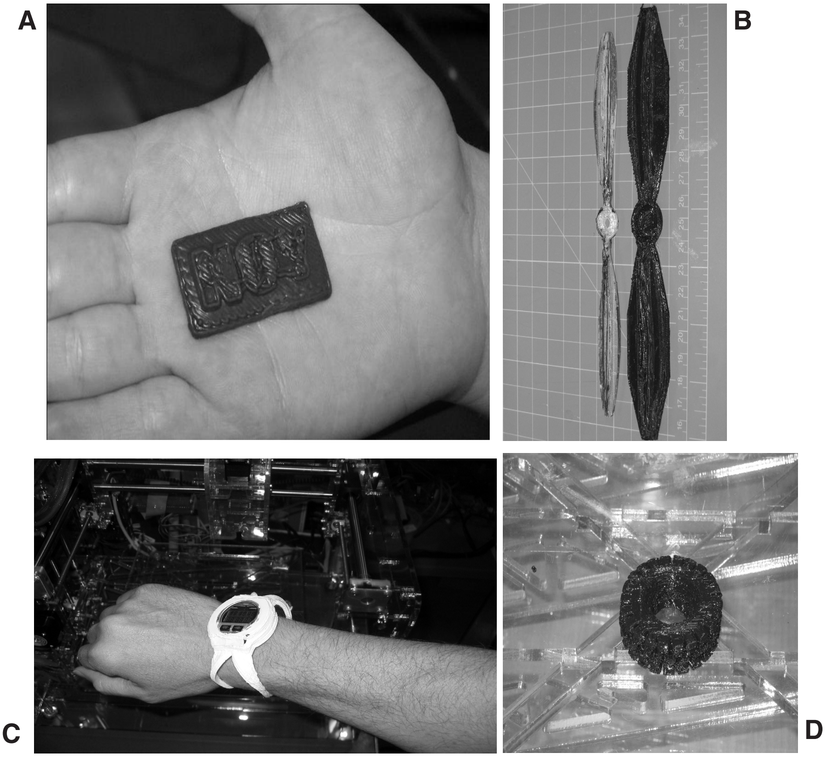


Fig. 6. Single material objects built with a FaH Model 1: (a) A personalized chocolate bar built with a modified Model 1 by Noy Schaal; (b) A mold for a model airplane propeller fabricated using 1-part RTV silicone rubber, and a propeller cast with epoxy from the mold; (c) a watch made by fabricating a silicone watchband and inserting a conventional watch body during the process; (d) a replica of a model car tire fabricated of black silicone rubber

Discussion forums are available using the free Google Groups service, and the source code for the project is shared via SourceForge, a free service which facilitates FOSS development. Through these media, participants in FaH have begun to exchange their ideas for applications and their improvements to the hardware and software with us and each other.

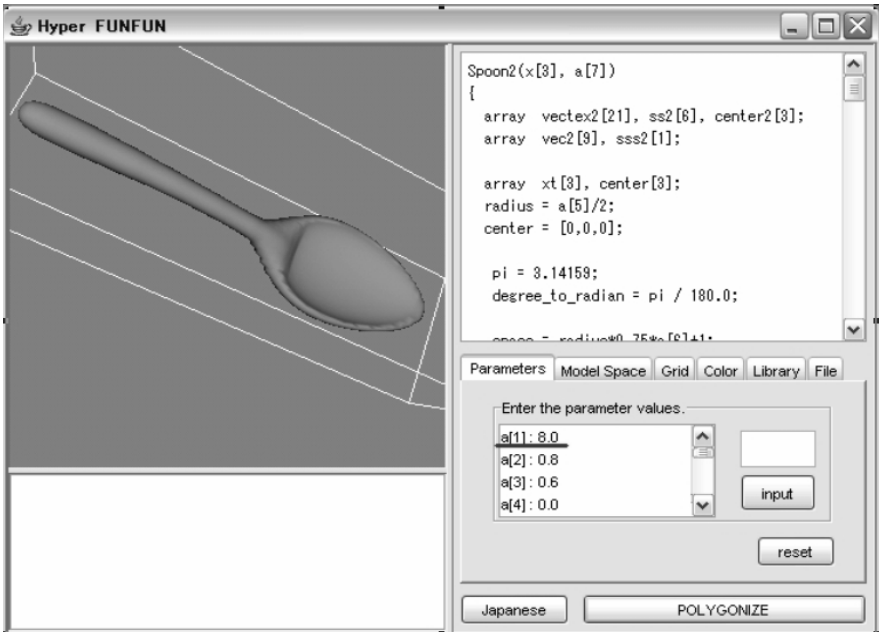
As evidence of the broad appeal of DF, and the potential impact of making DF more publicly accessible, in the first five months after October 2006 (when the website was first made publicly accessible), the project website had more than 3.5 million requests for pages from more than 150,000 distinct hosts in more than 150 countries. Users have begun to make contributions to the FaH wiki, the Google Group, and the SourceForge project in the form of new deposition process ideas, bug reports, questions, feature requests, alternative vendors, group purchasing arrangements, and more.

6.2 HyperFun

At the beginning of the personal computer revolution in the early 1980s there was a need to have a standard, generalized language for digital and desktop printing; the same need exists for DF today. The PostScript language was invented to answer the needs of desktop printing. PostScript is so noteworthy because it goes beyond typical printer control formats and is a complete self-contained programming language, allowing it to implement on-the-fly rasterization using interpreters (PostScript Raster Image Processors), making it extremely compact and device-independent. Like PostScript, HF is a completely self-contained, compact, and device-independent programming language for representing and constructing real objects. This feature as well as others makes HF well suited to become a “3D PostScript” for DF technologies.

In addition to being a programming language HF is a robust software framework, used to create, visualize, and fabricate volumetric 3D models. The platform includes several on-line, Web based rapid interfaces for accessible, collaborative and flexible modeling (Fig. 7). Unlike other modeling packages, it can easily model *heterogeneous* objects in infinite detail. HF is able to represent imaginary objects or capture real existing objects with all the properties and details found in reality and nature. Making this possible, HF is built using a new approach to computing with geometry called the Function Representation (FRep) (see other papers of this volume for more details). In contrast to other existing geometric models, FRep provides a uniform method to model both surface geometry and internal composition simultaneously. It is also a compact and precise framework that can represent objects with unlimited complexity and properties.

Formally a HyperFun object is defined by a vector-function, where each component is a real continuous function of point coordinates. The first component defines object geometry by the inequality $F(x1, x2, x3, ..., xn) \geq 0$. Other components of the vector-function define object attributes representing object's properties at the given point. The HyperFun language allows the user to define a geometric object and its attributes with the help of assignment statements (using auxiliary local variables and arrays, if necessary) as well as conditional selection and iteration statements in a



```
Spoon2(x[3], a[7])
{
  array  vectex2[21], ss2[6], center2[3];
  array  vec2[9], sss2[1];

  array  xt[3], center[3];
  radius = a[5]/2;
  center = [0,0,0];

   pi = 3.14159;
   degree_to_radian = pi / 180.0;
```

Enter the parameter values.

a[1] : 8.0
a[2] : 0.8
a[3] : 0.6
a[4] : 0.0

Fig. 7. A development environment for modeling on the Web

single function evaluation procedure. The functional expressions are built with using conventional arithmetic and relational operators, standard mathematical functions, built-in special geometric transformations and FRep library functions for primitives, operations, and attributes.

To our knowledge FRep/HyperFun is currently the only generalized framework and language for easily extensible, *heterogeneous,* volumetric modeling. In recent years it has gained popularity as the need for *heterogeneous* modeling grows. HyperFun.org develops tools for FRep modeling using the HyperFun language. It is an international, non-profit, FOSS organization. Members of the HyperFun team make a freely associated group of researchers and students from different countries all over the world (UK, USA, Russia, France, Japan, Norway, and others). The group has published more than 100 papers in academic journals and conferences, and develops and distributes software under a special FOSS license addressing human and environmental issues surrounding the dissemination of DF technology. Software tools supporting the HyperFun language are freely available at the HyperFun Project Web site (www.hyperfun.org) and source code can be found at SourceForge.net. To date the HF language and framework has been used to model a large number of single material, *simple* objects that have been fabricated using different techniques, from stereolithography to objects milled in wood (Fig. 8). In addition a variety of *complex* and *heterogeneous* objects have been modeled for visualization using HF.

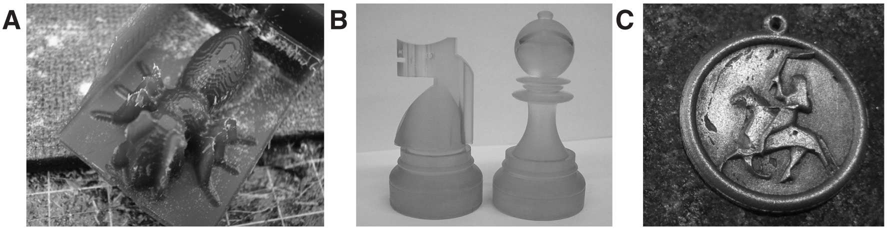


Fig. 8. Various objects fabricated using HyperFun: a) an ant milled in wax (about 3 mm long); b) a chess set fabricated using stereolithography; c) a Norwegian horse and rider crest cast in pure silver

As vector graphics and ideas behind PostScript made 2D desktop publishing and graphical interfaces possible and widespread, the ability of Frep and HyperFun to completely and compactly describe any 3D object has the potential to simplify complex desktop fabrication and physical interfaces, making them viable public technologies.

7 Experimental Work

Much of the goal of the research presented in this section is to bridge HF and FaH with additional development and in doing so, rapidly solve some of the issues outlined herein. The current objective is to directly drive and control the FaH equipment from HF software. Several FaH fabricators have been constructed by the HF and FaH researchers to enable this objective and additional development, both in Japan and Norway. Providing an easy means of directly driving the FaH from HF will mean that individuals can go from fabricating single material or *simple* (multi-material) objects to being able to fabricate *complex* and *heterogeneous* objects using the FaH.

The current FaH CAM software uses the STL file format to import objects and it is internally designed to operate on mesh based boundary data. As discussed above, this is an inadequate representation when fabricating *heterogeneous* objects, however the STL file format can be used to print *simple* objects.

7.1 Extending the Hardware for Multi-material Fabrication

The default FaH system is designed so that, besides the three axes required for Cartesian control, a fourth axis controls a plunger and a syringe with a single material, depositing exact amounts of material at a given location. It is possible to change out syringes during the fabrication process to create an object with more than one material; however this can be slow, very time consuming and is only practical for simple divisions of material. Recently the ability to add a fifth axis and a second syringe to the FaH has been developed (Fig. 9) along with an update to the FaH CAM software platform.

Work is underway to incorporate inkjet material deposition capability along with a single or dual syringe system (Fig. 10). An Inkjet Printing (IJP) head deposits material by ejecting small droplets of a solution at a given spatial frequency onto a substrate, allowing precise placement of relatively small volumes of these materials.

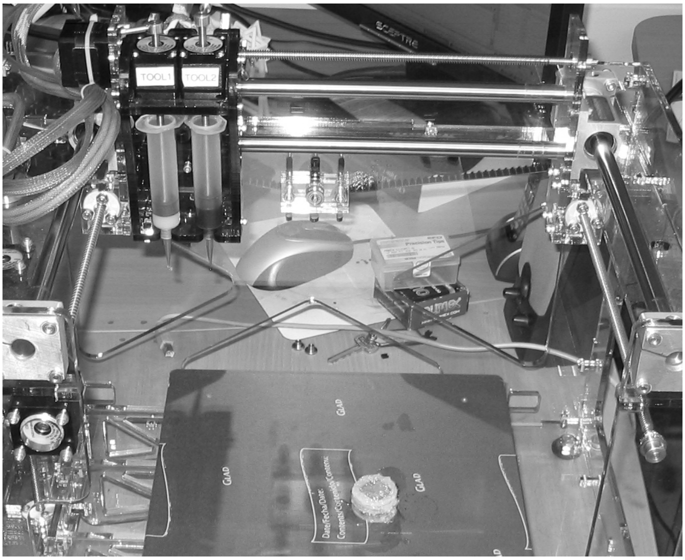


Fig. 9. The FaH multi-material fabrication tool and space

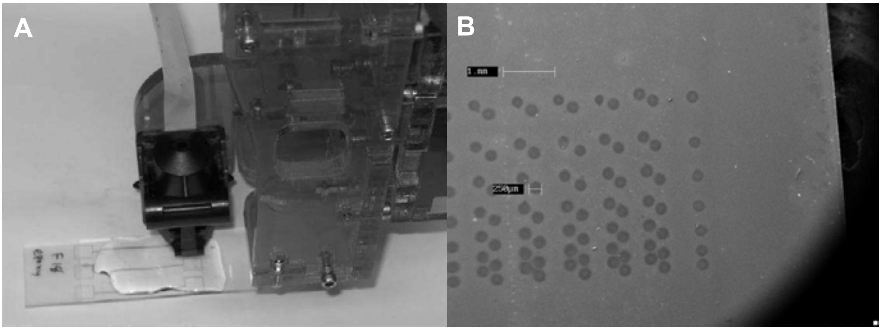


Fig. 10. (a) Inkjet head mounted on FaH along with syringe tool; (b) SEM image of droplet patterns deposited by inkjet with FaH

IJP has two main advantages over syringe deposition. First, such a tiny volume of material can be deposited (picoliters to nanoliters) with such high repeatability that material dries or solidifies very quickly, and lateral positional accuracy is determined almost entirely by the positioning system, rather than by material relaxation or flow. Second, achieving precise control of material flow from a syringe requires the syringe needle remain very close to, but not touching, the substrate, so that the deposited flow does not break irregularly into droplets and the needle does not collide with previously deposited material. This is exceedingly difficult to achieve without sophisticated sensing and feedback control. An IJP head, however, can remain several millimeters above the substrate, and hence is much less susceptible to destructive interactions with minor flaws in the object being fabricated.

Inkjet printing should be able to produce smaller and better-defined patterns of a material thus achieving greater object complexity or even heterogeneity than is possible with a syringe tool. The inexpensive inkjet system currently explored for FaH has lateral resolution (solidified droplet diameter) of 200-250 micrometers, but depending on the solids concentration of the ink used, we have observed vertical resolution (solidified droplet thickness) of 30-100 nanometers. More sophisticated systems can achieve lateral resolution of 25-50 micrometers. However, inkjets are restricted in the range of materials that can be deposited – materials must have a low and well-controlled viscosity, must be filtered to the micron-level, and materials must not solidify or precipitate solid phases within the head, or it will be destroyed. For this reason, it is clearly understood that the inkjet capability complements, but does not supplant, the syringe tool deposition method for the fabrication of *complex* or *heterogeneous* objects.

Due to these additions, the FaH is currently able to fabricate *simple* objects using the STL file format and the FaH CAM software. It is also now possible to fabricate arbitrary multi-material *complex* and *heterogeneous* objects given appropriate representations and control. Development is underway to control all five axes of the machine directly from code generated using the HyperFun framework.

7.2 HF Models Fabricated Using the FaH

Using the HF and FaH frameworks, several test objects have been fabricated including a horse modeled after a traditional Norwegian carving and a model of Darth Vader's head from Star Wars. Both of these objects were fabricated using a single material (Fig. 11).

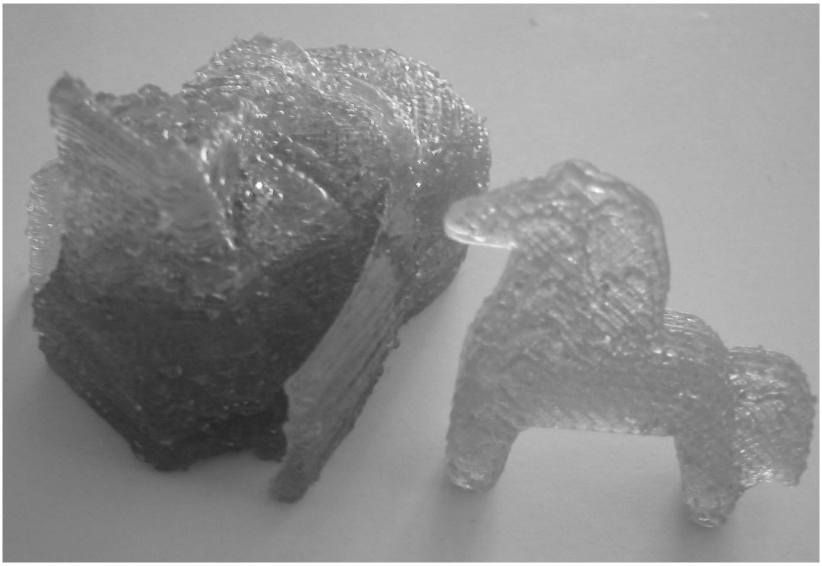


Fig. 11. Single material objects fabricated using HF and FaH

The fabrication path was generated by FaH CAM after importing STL files generated by the HyperFun framework. The CAM software had to be modified to handle the more complicated topology of Darth Vader's bust and generate the correct tooling paths. However, the short term development goal is to drive the FaH from HF for direct *hetrogenous* fabrication. The material used to fabricate these objects is a Norwegian construction adhesive, Ebofix which performed nicely in the FaH and resulted in nice semi-translucent objects. Both of these models where fabricated in the period of a day, Darth Vader's bust being, to date, the longest build for the FaH at almost nine hours.

7.3 Functional Multi-material Objects

A variety of functional models have been fabricated using the FaH including: batteries that are producing power even before the fabrication process is over, LED flashlight with a working switch (Fig. 12), toys that light up when pushed and electro active polymer actuator able to respond to electrical current by physical motion. Extensive use is made of the priority feature of the path planning software to reduce the number of tool changes in complicated multi-material object. For example, when fabricating a standard cylindrical battery, the battery case and the node conductor are set to the same priority, but higher than that of the other materials. The case and the anode conductor are deposited in a normal (non-backfill) layer-wise fashion, which allows the conductor to extend through an opening in the wall of the case for ease of connection. The FaH is extremely versatile multi-material fabricator capable of creating a wide variety of objects and utilizing a broad range of materials including epoxy, Ag-filled silicone, polyvinyl alcohol, alginate hydrogels and even chocolate.

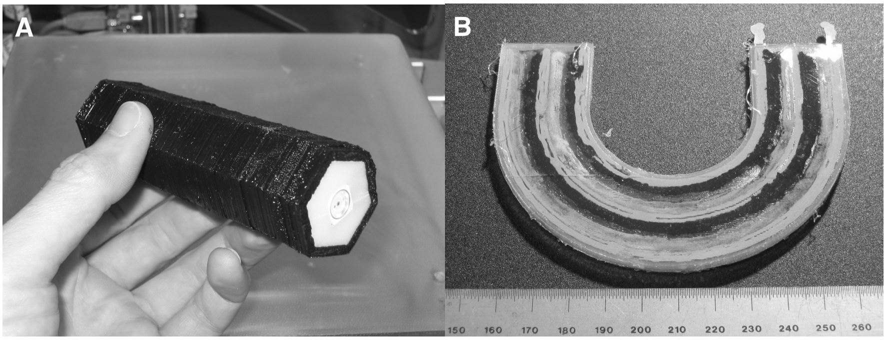


Fig. 12. (a) A fabricated LED flashlight with a working switch (b) and a fabricated zinc air battery

7.4 Complex and Heterogeneous Objects

Several models have been made on a Z Corp Spectrum Z510, a 3D color fabricator, to clearly demonstrate HyperFun's ability to represent and fabricate *heterogeneous* objects (Fig. 13). Although the object in Fig. 13 may look similar to objects modeled using traditional modeling software, it is important to understand that no texture maps were used to define or fabricate this object. It is purely a function-based model (see its detailed description elsewhere in this volume). Cross sections of the model are made at the resolution of the Spectrum Z510 and surface color (or even internal color) is derived from the composition of material modeled using HF.

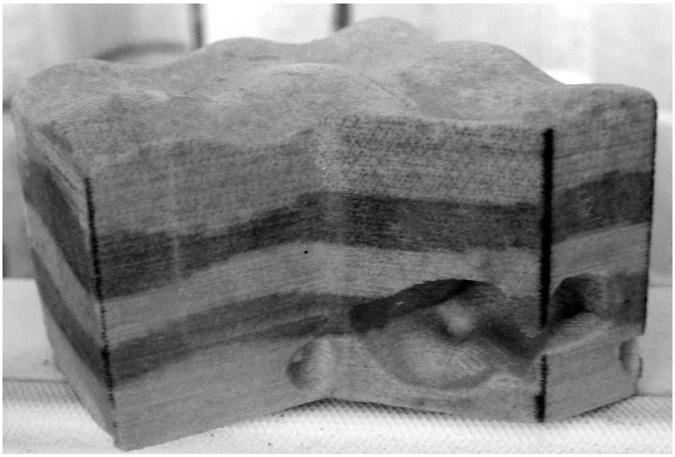


Fig. 13. HF Multi-material geology model fabricated on Z Corp Spectrum Z510

As the modifications to the FaH currently allow only to print in two materials, several new test models using two materials have been created to print with specific materials as good examples to demonstrate the difference between *simple*, *complex* and *heterogeneous* objects. Even using such a uniform and precise framework as HF, solving the issue of how to fabricate smoothly blended, *heterogeneous* objects on any given system can still require technological choices and solutions to be made. There are two approaches for using the FaH to fabricate such objects: blend the materials during fabrication or use some method of dithering between materials. Generalized code is being developed allowing for any method or type of dithering to be used. As HF allows for any number of properties to be assigned to any location it is also interesting to consider not only controlling the material distribution but the method of fabrication where several very different tools and/or processes can be used, each perhaps with several materials.

8 Discussion

Many of the implementation problems facing UDF remain unsolved and there is much work yet to do and new problems to discover. However, it is interesting to see just how far we can already come by simply adding a bit of glue between existing technologies and projects. It is also interesting to note the extremely low cost of the system proposed. With active work and a few additions, the current system can start to verge on a functional UDF.

The FaH, as of yet, does not blend materials on-the-fly and the deposition size of a given material is relatively large, so in some sense it can only practically fabricate *complex* and not *heterogeneous* objects. However, a variety of higher resolution and more sophisticated fabrication methods can be developed including blending materials before depositing them. Similarly the FaH tool options do not yet include a digital self-assembly tool. While the current hardware and software platform is not designed to digitally assemble objects, it will be possible in the near future to add such capabilities.

At present there are no accessible GUI tools for the modeling of *heterogeneous* objects with complex parts and relationships. HF lacks such an interface and users can not import or use existing models from traditional CAD systems with the standard HyperFun tools, so everything must be modeled anew. However, research and development exists that solves this problem. It will be possible in the near future to functionalize STL or other mesh data and use with the standard HyperFun tools as any other geometric primitive in the system. However, to truly make HF a usable part of a UDF system, additional GUI based design tools will be required. This is an active area of development.

The very real and serious issues of human and environmental hazards, although not covered here, will require earnest discussions and more active research. Input materials should avoid delivery to a UDF system in the form of powders or gases. Low toxic and bio-plastics should be considered for use in fabrication. It maybe possible to leverage the design freedom and complexity provided by UDF to redesign objects using biologically neutral and/or biodegradable materials and abandon the use of rarefied and toxic materials. Finally, the most important long term question to pose is can these complicated multi-material objects be disassembled back into parts or be recycled in some way. Environmentally, without the appropriate research and development behind better, smarter materials and fabricators, UDF could prove to be unsustainable.

9 Conclusion and Future Work

Inexpensive digital computation is allowing us to change the way we see and interact with the world and each other—to understand the world as heterogeneous and operate in and modify the world as such. We can now use computation to control matter, to design and fabricate "natural" solutions and objects. This has the potential to create products which are universally superior physiologically, environmentally, and functionally. Increasingly this is so because digital computation also makes it possible to instantly collaborate globally and share complex information, resulting in peer-based and localized designs. It puts the power of innovation into the hands of the few and the many at the same moment. UDF and similar technologies will change the way humans produce and consume goods, allowing individuals access, not to a factory or a superstore, but their own inexpensive and limitless digital workshop.

This digital epoch has already begun to take place, as a growing number of people invest in this technology and put it into action. We are continuing the development of the software and hardware of the Fab@Home Model 1 to provide performance and usability enhancements in anticipation of an onslaught of questions and complaints as the first wave of Model 1 users finish assembling and start using their machines. This will be a critical test of the survival of FaH, and we must ensure that we do not discourage these brave early adopters. Efforts will be directed to continued development of direct *heterogeneous* fabrication on the FaH, utilizing the HF framework. Modification to the FaH, sample object and code will be available on-line to let developers and users explore the new possibility.

Future development will be focused on improving the capabilities and integration of both hardware and software systems bringing together a complete UDF system. Development to build the next generation UDF fabricator and design tools are already underway. Ongoing UDF hardware research is developing digital self-assembly processes for the fabrication of objects by using materials with known properties and geometries. Software development will continue focusing on the creation of a complete UDF GUI modeling and fabrication software suite based on FRep and HyperFun technologies.

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